Chapter 1
Introduction

Tracking of vehicles in deep space, that is, at lunar or planetary distances, is accomplished through a variety of radio and optical techniques. Since the 1970s, the particular mix of data types used for interplanetary navigation has depended largely upon where the spacecraft was located along its flight path. For example, during the cruise phase of a mission, roughly from the time of injection into the interplanetary transfer orbit until approach to the target body, Earth-based radiometric tracking techniques are typically used. Radio tracking systems are called upon to provide highly accurate orbit information to support midcourse trajectory corrections and early probe releases. During the approach phase, these Earth-based observables may be used in conjunction with onboard optical images of the target or one of its satellites against a known star background. The optical images provide a direct measure of spacecraft position relative to the target and are an important complement to Earth-based radio tracking, especially when there is a large uncertainty in the target-body ephemeris.

There are some notable exceptions to this standard model for navigation tracking. In fact, a number of recent missions designed with tight cost constraints have relied solely upon radio tracking, even during the encounter phase, for example, Mars Pathfinder, Mars Climate Orbiter, and Mars Polar Lander. And the New Millenium mission Deep Space 1 (DS-1) successfully demonstrated autonomous, onboard cruise navigation, using optical-only measurements [1,2].

Future missions will use a mix of tracking data types appropriate to meet specific project requirements. These missions will benefit from the availability of a variety of precise, reliable tracking techniques to enable more challenging navigation performance or to provide complementary information in unexpected, difficult spaceflight situations.

This monograph focuses primarily upon the fundamentals of Earth-based radiometric tracking as applied to deep space navigation. Basic concepts of orbit determination are introduced in Chapter 2. A standard reference frame is defined; parameters that constrain a spacecraft trajectory are identified; and standard models associated with Earth-based tracking are discussed.

Until the 1980s, deep space radio tracking relied solely upon Doppler and range systems. The improvement in performance of these systems is reviewed in Chapter 3. The information content of each measurement is also discussed, and limiting error sources are identified.

Inherent limitations to conventional Doppler and range tracking prompted the development in the 1970s of a technique known as very long baseline interferometry (VLBI). This technique, already well known to radio astronomers, was first applied to spacecraft tracking during the late 1970s and was subsequently used by the Voyager project to support the Uranus and Neptune encounters. The VLBI system developed for navigating missions such as Galileo and Mars Observer in the 1990s provided a direct geometric measure of spacecraft angular position—in some situations, at least five times more accurate than that determined from several days of Doppler and range data. VLBI tracking concepts are introduced in Chapter 4. The advantages of this data type for angular positioning are described, and major error sources are identified.

Missions beyond the year 2000 will have ever-increasing requirements for improved radiometric tracking performance. These missions will be faced with issues related to navigation system robustness, reliability, and timeliness, as well as accuracy and cost effectiveness. Expected needs for rapid, onboard responses will place new demands on both optical and radio tracking technologies. Chapter 5 examines expected radio tracking system improvements motivated by expected future challenges, such as tight targeting requirements at Mars to enable aerocapture and precise descent and landing, navigating low-thrust missions with imperfectly modeled spacecraft forces, and precisely landing a sample return mission on Earth.

References

[1] S. Bhaskaran et al., "In-flight Performance Evaluation of the Deep Space 1 Autonomous Navigation System," MS00/53, *Proceedings of the International Symposium on Spaceflight Dynamics*, Biarritz, France, June 26–30, 2000.

[2] J. E. Riedel et al., "Using Autonomous Navigation for Interplanetary Missions: The Validation of Deep Space 1 Autonav," IAA-L-0807, *Fourth International Conference on Low-Cost Planetary Missions*, Laurel, Maryland, May 2–5, 2000.